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Dual-Layer Beamscanning Reflectarray Antenna Operating at Ku-Band

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Abstract

This paper presents a beam scanning electronically reconfigurable reflectarray configuration for Ku-band applications using a single varactor diode. A 15×15 center-fed reconfigurable reflectarray antenna is designed consisting of 225 octagonal-shaped unit cells. The proposed tunable element has a unit cell size of 9.8 mm, developed on a 1.575-mm thick Taconic TLY-5 substrate. A single varactor diode is integrated with the tunable element to produce a reflection phase variation of 340° at 14.1 GHz. In this work, both the varactor and biasing circuit are placed beneath the substrate to avoid unexpected reflections, which leads to achieve a pencil beam of 8.1° beamwidth. The simulation results of the reconfigurable reflectarray antenna (RRA) show good beam-scanning radiation performance of scanning range ±30° and a peak gain of 27.6 dBi. The RRA offers a simulated gain of 27.3 dBi with a side lobe level of -14.3 dB and cross-polarization of -24dB at 14.1 GHz. This structure provides a convenient solution for Ku-band distinctive applications such as uplink operation in the direct broadcast satellite system, digital video broadcasting, earth exploration satellites, space research satellites, and defense systems.

Keywords: *Beam scanning; Reflectarray; Reconfigurable; Varactor or varicap diode;Ku-band*

1. Introduction

Microstrip reflectarrays developed as low-profile printed antennas coalesce the advantages of parabolic reflectors and phased arrays. The reflectarray by inheriting the advantages of reflectors and phased array is well suited for high-gain beam scanning antennas. Generally, reflectarray consists of radiating elements that are spatially fed by a primary feed, by which the properties of the electromagnetic field are altered, thus introducing a phase shift to accomplish the desired radiation pattern. Different reflectarray configurations have been proposed in the literature, each one based on the idea of varying one or more geometrical/electrical parameters of the single radiator, providing a proper change in the reflection phase (Pozar, 2003). Striking features, such as lightweight, low cost, easy to fabricate, suitable for batch fabrications, easy to mount, etc. (Huang and Encinar, 2007), have made RRA evolve into a provocative candidate for distinct applications such as military applications, high-resolution imaging radars, remote sensing, weather monitoring,

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backhauls, maritime vessel traffic control, defense tracking, air traffic control, and vehicular speed detection, etc.

Reconfiguration in reflectarray is achieved by reforming its properties such as frequency, radiation, and polarization in a dynamic and controlled manner. Generally, the beam formation of the reflectarray can be scanned by means of feed system or altering the array nature of antenna. Because beam scanning using feed system is limited to few scanning angles, altering the aperture phase provides wider scanning angles. The aperture phase can be altered by using active devices like PIN diodes, varactor diodes or MEMS switches. Such reconfiguration is accomplished by employing electrical, physical, and mechanical actuators or tunable materials that enable the intentional modifications of its properties. Even though in traditional reflectarrays, the desired radiation pattern is achieved by modifying the printed characteristics of the individual elements yet beam scanning is achieved using electronically tunable microstrip elements.

A mechanical approach opted in (Fusco, 2005) using miniature motors for the element's rotation and the displacement of a dielectric rod under each radiator had major drawbacks of increased motor size and cost. Another category of electronically tunable elements, MEMS switches used for beam scanning performance covering the full 360° phase range are presented in (Bayraktar et al., 2012), (Guclu et al., 2012), (Perruisseau-Carrier and Skrivervik, 2008) & (Wu et al., 2008). In (Bayraktar et al., 2012), circularly polarized RA inheriting six equally spaced series RF-MEMS switches, implement the sequential rotation required for attaining the desired phase range. The proposed RRA is capable of switching the beam between broadside and 40° with a measured gain of 11.42 dBi at 26.5 GHz. In (Perruisseau-Carrier and Skrivervik, 2008) & (Wu et al., 2008), the MEMS switches are controlled digitally to provide beam scanning in RA. MEMS devices although have merits like very low loss and negligible power consumption; still, complex design and cost become a serious impediment to MEMS usage. In addition, utilizing the advantage of simplified biasing circuit requirements, tunable materials such as graphene and liquid crystals are used in (Hu et al., 2008), (Perez-Palomino et al., 2013) & (Perez-Palomino et al., 2015) to achieve reconfiguration in RAs. In (Perez-Palomino et al., 2015), an RA developed on the lower surface of quartz crystal with 54×52 multiresonant cells produce beam steering of 55° at 100 GHz. Still, the fabrication of graphene-based RA and the integration of crystal materials in the reflectarray panel are challenging. Furthermore, simplification in reconfiguration was made using PIN diodes reported in the literature (Shi and Zhang, 2017), (Kamoda et al., 2009), (Carrasco et al., 2012) & (Li and Abbosh, 2015). In (Carrasco et al., 2012), a 64-element pattern reconfigurable RA is developed using a circular ring connected to an arc stub providing 450° phase variation. The PIN diode connected between the two parts of the arc stub provides a beam steered to 22° at 4.05 GHz and 30° at 3.75 GHz with a measured peak gain of 14.1 dBi and 14.5 dBi, respectively. A 1600-element frequency RRA assembled as five identical subarrays provide an increased gain of 29.3 dBi and 30.8 dBi at 11.1 GHz and 14.3 GHz, respectively. The frequency reconfiguration is achieved by controlling the PIN diode connected to each element using an integrated DAC board. Although PIN diodes are advantageous in having fast switching, and constant DC characteristics, they suffer from drawbacks, such as high-power consumption and lack of continuous tuning.

Owing to the continuous scanning and low power consumption nature of varactor diode, as compared to other active devices like PIN diode and MEMS switches, the researchers in (Nie et al., 2016) have used varactor to provide a higher degree of reconfigurable performance. The proposed RA provides continuous beam steering between -60° and +60° at 12.1 GHz. However, the design has a major drawback of 8 layers of stacked configuration rendering high cost. A similar beam scanning performance using varactors is reported in (Venneri et al., 2012a), (Venneri et al., 2012b), (Venneri et al., 2013b), (Venneri et al., 2013a) & (Abdelrahman et al., 2017), where the unit cell design is based on the aperture-coupled approach. This design still increases the complexity of the design due to placing the diode inside the stack configuration. As an improvement over design complexity, a single-layer configuration is reported in (Liu and Hum, 2010), with a concentric square patch having six varactors incorporated on the top surface, having increased cost as a demerit. By reducing the number of diodes, papers (Liu et al., 2018), (Hum et al., 2007) & (Hum et al., 2005) have reported the use of two diodes on each reflectarray element to achieve a full phase tuning range. In 2012, a single layer single varactor, C shaped (Zainud-Deen et al., 2012), 21 × 21 array was presented with a diode placed inside the configuration which leads to

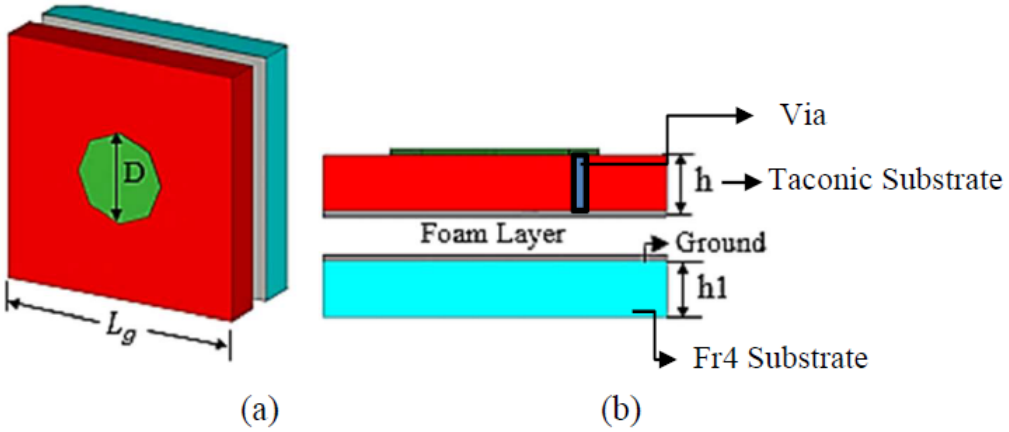

Figure 1. Reflectarray element: (a) front view and (b) side view

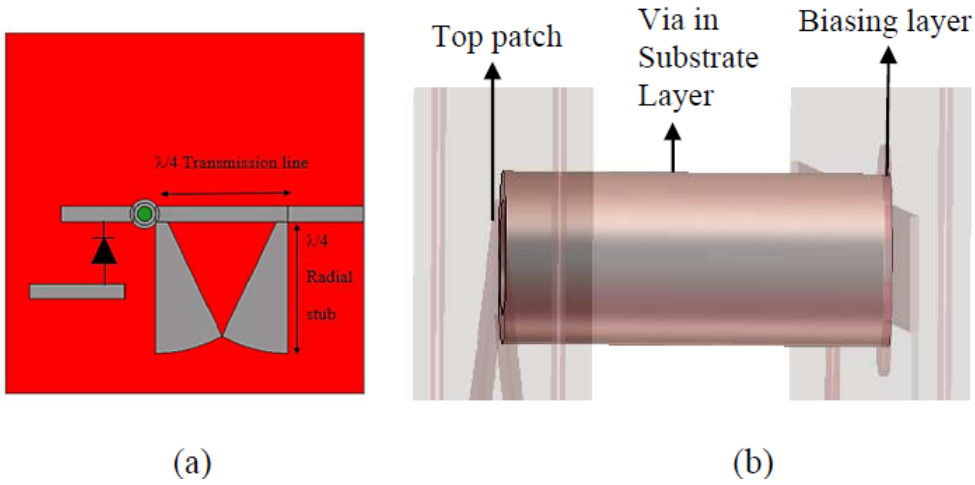

Figure 2. (a) Back view of the reflectarray element (b) Expanded view of Vias

design complexity. Further, in the paper (Tayebi et al., 2015), a 10×10 dual band single diode concentric patched array was providing a 330° phase range. However, despite their good phase agility, the above configuration is characterized by a reflecting surface with several discontinuities due to the presence of varactor diodes, biasing circuitries, and soldiers, which in turn may create undesired scattered field components. Based on the study made through the literature survey, a configuration having an electronically driven single varactor diode, biasing circuitries, and soldiers on the opposite side of the reflecting element are essential to avoid unexpected reflections. This work aims at achieving reduced spurious radiation, improved sidelobe level, and antenna efficiency by placing the varactor underneath the first substrate. Hence in this paper, the design of a reflectarray prototype with beam-scanning capabilities is discussed to validate the approach. The designed pattern reconfigurable reflectarray antenna is properly tuned using a varactor diode to obtain pencil beams at different scan angles between ±30°. The presented prototype is composed of 15×15 elements, each one loaded by a single varactor diode integrated with an electronic DAC board to supply the required reverse bias voltage. In addition, out of different reconfiguration techniques, the beam scanning is crucial due to its usage found in many applications such as radar emergency communications, earth observations from space missions, geophysics aircraft model, etc. The paper is organized as follows. Section 2 describes the design and characterization of the single reflectarray element. The implementation of the reflectarray antenna design is presented in Section 3. Section 4 explains the simulated and measured results of the proposed reflectarray structure.

The design and performance characteristics of the array are also summarized in this section.

2. Design and Characterization of Refeflectarray Element

Based on the study made, factors like the structure, size of the radiating element, the material and thickness of the substrate, the number of layers, and the thickness of the air layer affect the reflection characteristics. Hence, after analyzing various substrates of different thicknesses, the substrate material and the basic structure of the radiating element are determined. The proposed reflecting element consists of an octagonal metallic patch of diameter $D = 2.675mm$ printed on the dielectric material Taconic TLY-5 ($\varepsilon_r = 2.2$, $\tan\,\delta = 0.0009$) whose thickness $h = 1.575mm$. The biasing circuit and the varactor are placed immediately after the substrate to avoid unwanted reflections. Between the ground and the Taconic layer, an air gap of 2mm thickness is present for the improvement in bandwidth and to reduce the quality factor. The vias are placed between the patch and biasing circuit to connect the top layer to the biasing circuit. Underneath the air gap, a perfect electric conductor (PEC) ground of length $L_g = 9.8mm$ and thickness of 0.035mm is used with the dual purpose of reducing the back radiation as well as eliminating any unwanted coupling between the electronic control board and the radiating structure.

For rendering additional support to the ground, FR4 ($\varepsilon_r = 4.40$, $\tan\,\delta = 0.02$) substrate of thickness $h1 = 1.6mm$ is appended. Figure 1 depicts the proposed unit cell structure and its layers. The required phase compensation for generating a pencil beam in the desired direction is obtained with a single varactor diode implemented on to the bottom part of the upper substrate. The position of the varactor on the substrate is illustrated in Fig. 2. The equivalent parameters of this diode are presented in Table 1.

Table 1. Equivalent Parameters of Skyworks Varactor Diode, SMV 2019-07LF

Parameter	R	L	C
Value	4.8 Ω	$0.7nH$	(0.16 to 2.254pF)

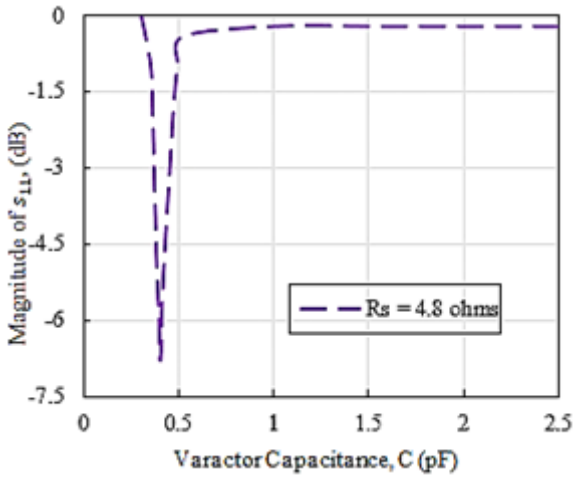

Figure 3. The magnitude of the reflection coefficient sub-11V_s diode capacitance computed for the diode resistance R_s

The varactor diode loaded with the radial stub causes the change in stub input impedance in response to the varying varactor capacitance. This causes a change in its resonant frequency which in turn varies the phase of the reflection coefficient. To provide isolation between the DC biasing and RF signal, a quarter wavelength transmission line and a cat ear radial stub are designed as shown in Fig. 2. Generally, the tunable line behaves in two aspects: an open circuit for lower values of varactor capacitance and an inductive load for higher values of varactor capacitance. Also, a reduction in the magnitude of the reflection coefficient occurs due to the series resistance of the

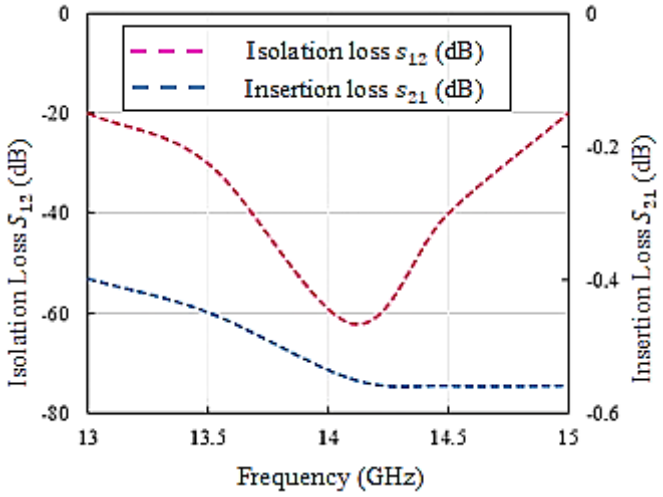

Figure 4. Simulated scattering parameters S_{12} and S_{21}

diode resulting in maximum losses occurring at the line resonance condition. This in turn affects the total reflection loss. However, this negative effect can be reduced by choosing a diode with a lower series resistance, as illustrated in Fig. 3. Thus, Skyworks Varactor diode, SMV 2019-07LF as in (Luo et al., 2019) is loaded with the patch. The junction capacity C of the varactor varies in the range between 0.16 pF and 2.245 pF as the applied reverse bias voltage varies from 0 to 20 V. In this way, the coupled line behaves like a tunable LC circuit achieving high insertion loss and low isolation loss as schematized in Fig. 4. Based on the work reported in (Cwiklinski et al., 2018), a radial stub with cat ears having an arc length of 45° and a line width of 0.4 mm is designed for the operating frequency. This structure is an alternative to conventional radial stubs in terms of isolation improvement and size effectiveness. Thus, the biasing circuit designed is considered a good option due to the difficulty in finding lumped components at Ku and X-bands, and an intrinsic impedance of 90 Ω is coupled to the tunable element through metallic via. The simulated curves reported in Fig. 5 demonstrate a phase tuning range of about 340°, within the frequency range from 13.5 GHz up to 14.7 GHz.

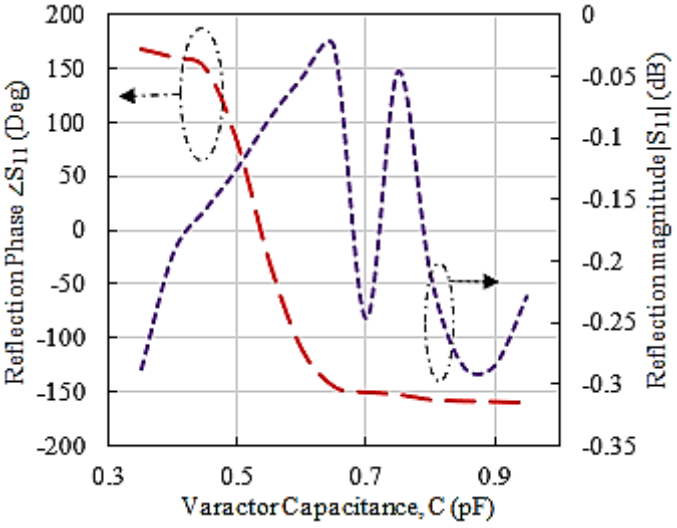

Figure 5. Reflection characteristics of the proposed unit cell as a function of the variable capacitance

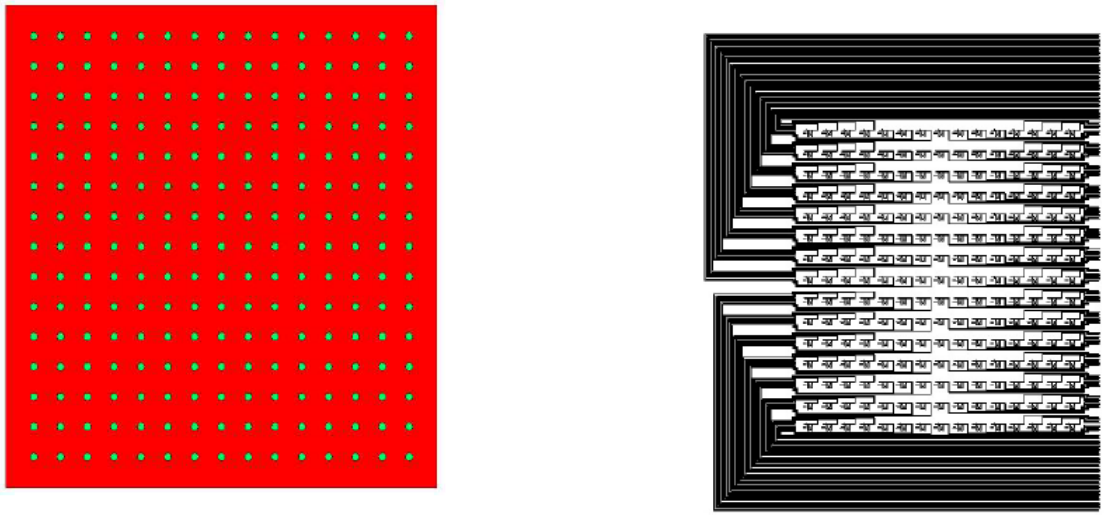

Figure 6. Biasing circuit of the reflectarray prototype (a) Front view (b) Back view

3. Implementation of Reconfigurable Reflectarray Antenna

Based on the simulated results of the unit cell, a 15×15 reconfigurable reflectarray incorporated with a varactor diode in each element is designed considering a periodicity of 9.8 mm $(0.45\lambda_0)$. Thus, the 225 elements of the reflectarray are set on a square plane geometry of $157.5mm \times 157.5mm$ size. The ratio of focal length to aperture size (i.e., f/D) known as "f over D ratio" is an important parameter used in reflectarray. Its value varies from 0.6 to 0.1. Hence, the optimum distance $f/D = 0.8$ (126 mm) is chosen as focal distance between the horn and reflectarray. The Matlab code is used that imparts the reflection phase range along with the positioning of elements at different locations in the array. Similarly, the S−curve depicts the relationship between reflection phase versus radius of octagonal ring. Using the S curve plot, the respective radius for each reflection phase value can be obtained. Further, the position of each octagonal ring is mapped by matching the reflection phase from both S curve and Matlab code. After mapping process, the array of 225 elements is divided into four quadrants and array elements are constructed initially on the $1/4^{th}$ side of the quadrant containing 56 elements. Because the array is symmetric along both directions, these 56 elements are mirrored in both X and Y directions; thereby, containing 225 elements. Using this phase distribution table, the required capacitance for each unit cell is determined by comparing the reflection phase curve obtained from CST. Thus, the 225 varactor diodes in the array are used to switch between the different phases to accomplish beam scanning. However, at such a high frequency, the loss and phase shift induced by the diode has to be considered carefully. Fig. 6 (a) is the schematic representation of the reconfigurable reflectarray antenna designed. As shown in Fig. 6 (b), each end of the open-ended stub is connected to biasing lines through which the voltage is applied to each varactor.

4. Results and Discussions

The capacitance values expressed in picofarad computed for different beam scan angles $\theta = \pm 30°$ from the Matlab are shown in Fig.7(a – f) and which clearly explain the beamforming concept for different angles. The simulated radiation patterns show the validity of the proposed approach, as the main beam is successfully moved along the desired directions. The array grid spacing, in conjunction with the array size, allows us to actively move the radiated main lobe along all directions ranging from $\pm 30°$, without occurring in grating lobe appearance. As the H-plane first null beamwidth is equal to 6.1°, along with the sidelobe level occurring at -13.7 dB when driving the varactors reverse bias voltages are achieved. The simulated polar plot in Fig. 8 portrays the

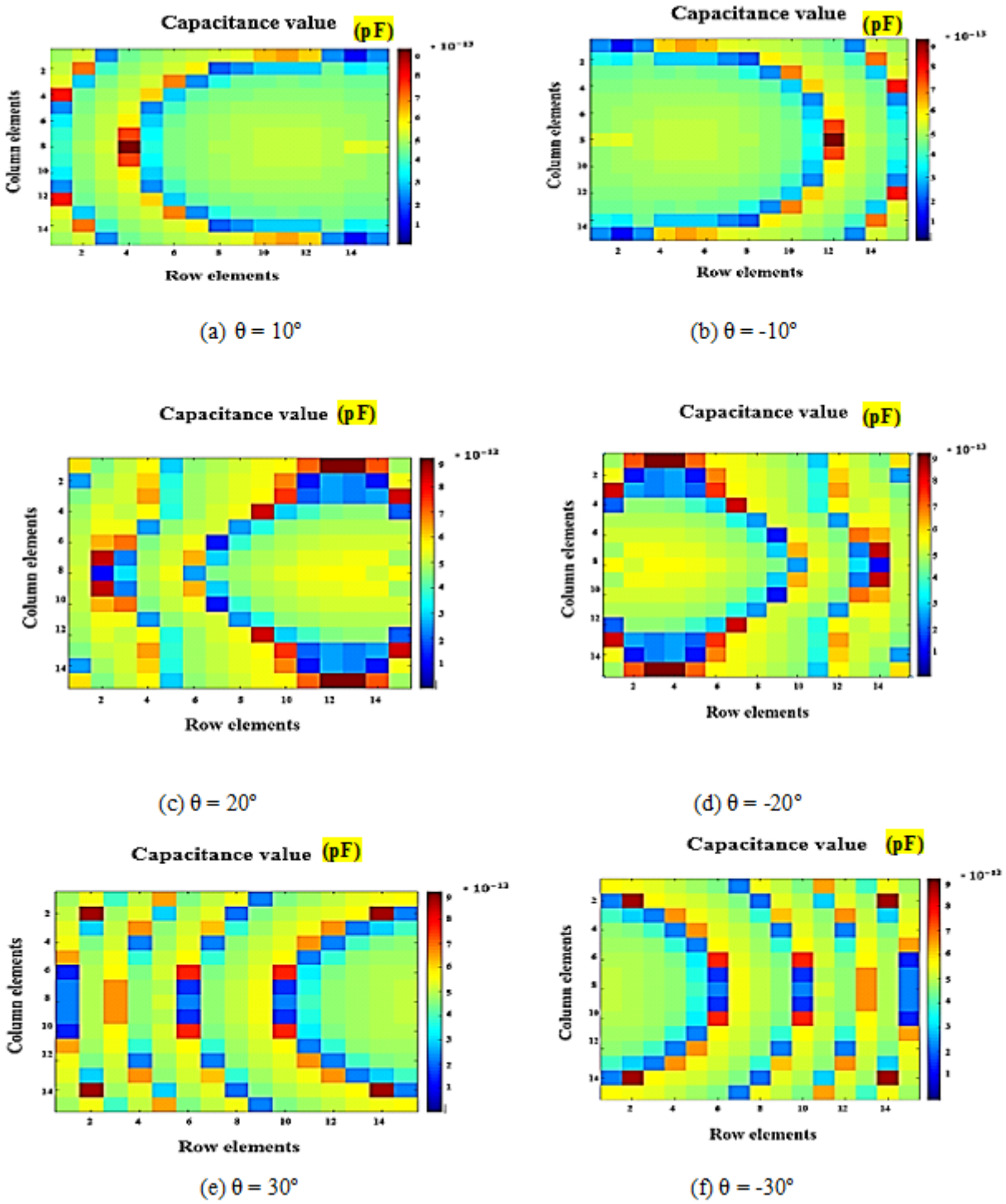

Figure 7. Synthesized capacitance value for (a) $\theta = 10°$, (b) $\theta = -10°$, (c) $\theta = 20°$, (d) $\theta = -20°$, (e) $\theta = 30°$, (f) $\theta = -30°$

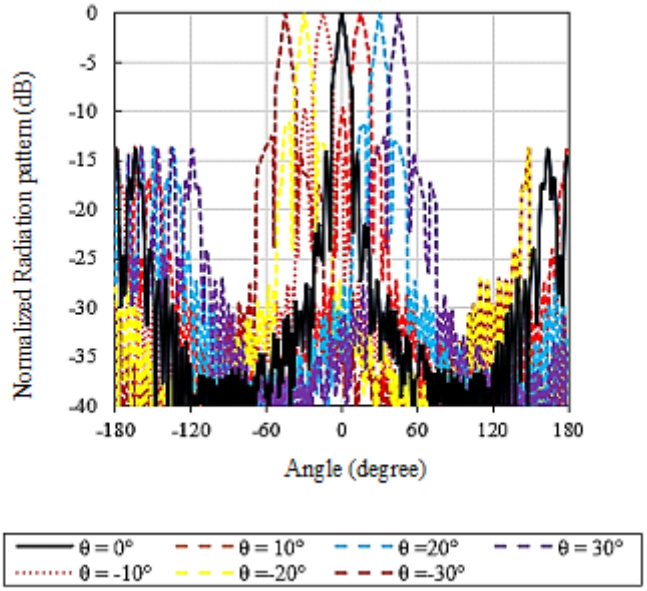

Figure 8. Simulated radiation pattern at ± 30° degree

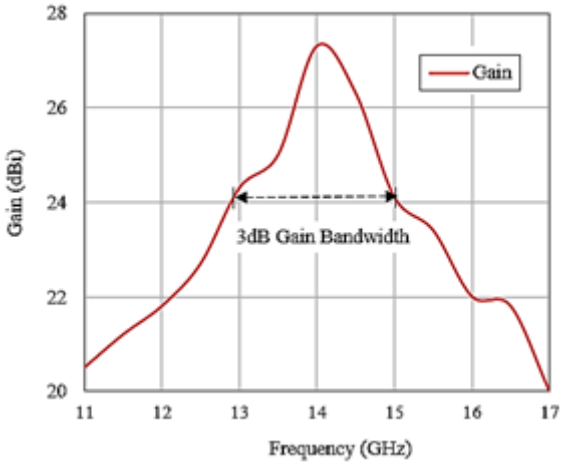

Figure 9. Simulated gain vs frequency plot for the reflectarray prototype

beam tilt that occurred at different scan angles due to applied reverse bias voltage. The measured peak gain of the RRA at 14.1 GHz center frequency is 27.56 dB along with -3 dB gain bandwidth measured as 5.37 %. The gain vs. frequency plot is shown in Fig. 9 with the inclusion of frequency range from 11 to 17 GHz. The 3dB gain bandwidth is covered from 12.9 to 15GHz, wherein there is a gradual gain decrease in both sides of the specified frequency range.

5. Conclusion

A radiating octagonal patch element is developed on the Taconic TLY-5 substrate with the permittivity of 2.2 and a phase response of 340° is obtained from the unit cell tuned by a single varactor diode. Using the radiating element, a 15x15 reconfigurable reflectarray element is designed with the varactor diode loaded on the bottom surface of the substrate. Simulated data are reported to demonstrate the phase tuning ability of the proposed configuration operating in the Ku-band. The varactor biasing voltages are properly synthesized to reconfigure the H-plane pattern within ±30° angular range. A pencil beam with 6.1° beamwidth and a sidelobe level of -14 dB is obtained and the maximum simulated gain of 27.3 dBi using 225 octagonal patch elements. When compared with the previous works, analyzed in the literature survey, this paper achieves a gain of more than 20 dBi in the operating frequency.

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